On aspects of System Analysis and Dynamics workflow

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Abstract

The workflow in System Dynamics may be seen to follow certain general flow patterns within the adaptive-iterative approach required. We constructed some diagrams to gain transparency and understanding of different tasks in the modelling process. The modelling workflow involve systems analysis, group modelling and system dynamics. The systems analysis as executed during group modelling consists of three model building stages and one implementation task. The stages involve Definition, Clarification, Confirmation and Implementation. After defining the issues and questions, the process evolves the Causal Loop Diagram (CLD) iteratively with the Stock and Flow Diagram (SFD), which form the construction drawings for the programming of the model incorporated as a System Dynamic Tool Diagram (SDTD). The third stage is the testing of the computerized model version created by the System Dynamic tool (SD-tool) and the fourth task is the implementation of the outputs into results and policies. This may be considered as an iterative process in all the stages. Innovation is the emergent output from a process operating according to the learning loop: Finally the roadmap given to our students for going from question to model diagram is shown.

1. Introduction

Walker (1923) and later Hougen and Watson (1946; 1948) developed the stock-and-flow diagram as a general representation of chemical engineering production systems, in order to help structure and organize the equation systems used for modelling chemical processes in the industry. Much later, Forrester (1968), developed the Causal Loop Diagram (CLD) concept as a part of communicating the complex SFD structure into simplified feedback structures. The CLD was initially regarded as a posterior tool for describing a 'ready made' simulation but it was soon discovered that a CLD could be used as an aid for conceptualising a hypothesis for a problem (Randers, 1980). Although a model building is an iterative process, qualitative models (mental models), precedes the step of constructing a simulation in a computer (Haraldsson and Sverdrup, 2003). We have explored the issue in earlier work (Haraldsson and Sverdrup 2003, 2005, Haraldsson et al 2005), terminating in our definition and interpretation of the method called "the learning loop".

2. Purpose and scope

The purpose of this text is to discuss aspects of organizing the workflow in modelling using systems analysis approach towards system dynamics. Furthermore to illustrate how the modeller can make use of check list to inspect the iterative modelling process from a qualitative model into a quantitative and computerized numerical model. The analysis is partly based on

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experiences and experiments from the period 1997-2005 with teaching systems analysis at the LUMES programme at Lund University.

3. Problem formulation and qualitative CLD analysis

Conceptual analysis is the starting point of the modelling process. There are several different qualitative techniques that are available when creating the mental model, including features such as mindmaps, parameter lists, situation drawings, causal loop diagrams (CLD) and stock and flow diagrams (SFD) and Systems Dynamics tool diagrams (SDTD) (Richardson and Pugh III, 1981; Roberts *et al.*, 1983; Ford, 1999; Sterman, 2000) to name few, and Rich-Picture (Checkland, 2000). Any method is good, as long as it illustrates the structure of the problem, and facilitates the necessary understanding to deal with it, thus it must communicate well. One of the most important features to extract out of a mental model are feedbacks. A mind map is a structural mapping including connections, however it has no illustration of feedbacks, not always any directions and there is no priorities or valuations put into it. It can be said to be a pre-stage to the causal loop diagram that will emanate after sorting and prioritising. The CLDs are good in that manner since they specifically illustrate the feedbacks and allow 'back of the envelope' analysis of problems. Experiences from the Swedish LUMES programme (Where the authors have been teaching systems analysis since 1997) has shown that the CLD is a good tool for mental model communication between persons with different ethnic, cultural and academic background. Working successfully with the mental models requires that several steps are followed through (Haraldsson and Sverdrup, 2003; Haraldsson, 2004). These are:

1. Define the problem and create the system boundaries.
2. Ask the question, state explicitly the purpose and goals.
3. Sort main variables in the problem and list them according to hierarchal order.
4. Draw the Stock and Flow Diagram (SFD), then the Causal Loop Diagram (CLD) and test them against each other. Question every link, ask for every link about possible back-links
5. Draw Reference Behaviour Pattern (RBP) as derived from the CLD and SFD and compare this to the Observed Behaviour Pattern (OBP) as derived from experiences.
6. Test if assumptions are reasonable in the CLD and SFD
7. Learn and revise by going back to point 3.
8. When the questions can be answered to satisfaction: Conclude, document and implement the results

The CLD communicates the feedback structures in a problem, displaying causal links pertaining to differential changes in states and change rates. A CLD forces the modeller to state a specific question about the problem as well as state the boundaries around it, as well as exposes the fields of lacking insight or information. Our experience is that by developing a stock and-flow diagram for the process simultaneously, the "plumbing" of the system is investigated and documented. Because the two are related and must be consistent, iteratively going between them help define both CLD and SFD. These together form the design drawing for the computerized version of the model, such as transfer to a System Dynamic Tool Diagram (SDTD). The SDTD is used in SD-tools to show flows and fluxes in the system as well as the feedback mechanism. SDTD is thus a hybrid of the CLD and SFD where the CLD are integrated features within the diagram. This is a required feature of the SD-tools in order to handle the numerical domain in the model. The process is exited at the earliest point possible with respect to answering the stated question and purpose of the effort. If the accuracy of the answer is sufficient with a mental model (oral story, picture, text, CLD, SFD), then there is no need to continue with a computerized version of the model. The mental modelling step can be considered as the most important step, from which everything thereafter emanates. A computerized version of the model is only a high performance numerical version of that same mental model. Before constructing the CLD the problem needs to be clearly stated. That is, the system boundaries and the question to be answered are formulated prior to the other steps. Thereafter, the problem variables are sorted, where the variables that are supposed to be included into the CLD and categorised into; agents which comprise active agents precipitating actions, and passive agents being commodities or entities being transformed, moved or destroyed, in a SDTD pictured as connection points for decisions, stocks for countable entities, actions which are precipitated by active agents and decisions in the system, 'conditions' being important controlling or limiting factors acting into the system from without the system boundary. This information is important since feedbacks and delays have different properties depending on if the variables are informational or physically related. These are also special properties of the variables that are used for converting a CLD into an SFD.

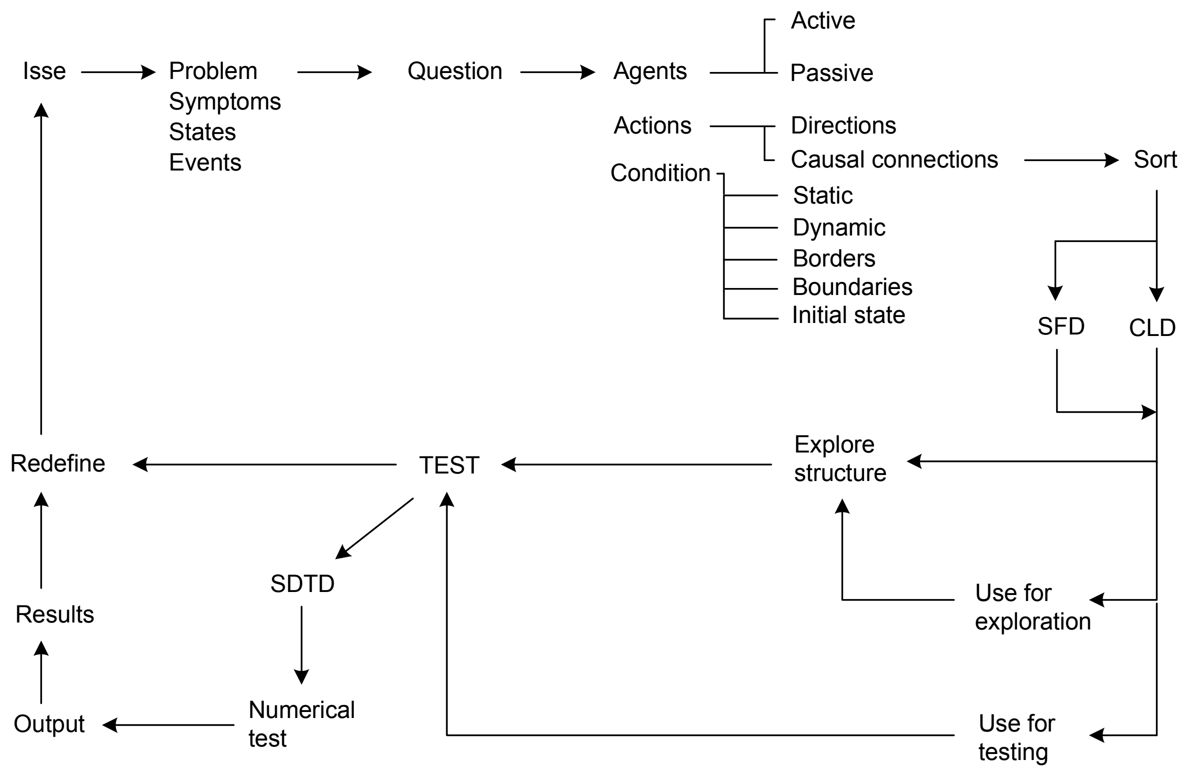


Fig. 1: The workflow in using Systems Analysis approach to Systems Dynamics model development.

The sorting stage prepares the identified variables into the CLD and SFD structure. The iterative between the CLD and the SFD structure enables the user to explore the structure for analysing its fit towards the question. The testing of the CLD and SFD determines if the model is ready for the SD-tool in the form of SDTD or if the structural analysis redefines the issue, Fig, 2. The definition phase needs to consider scale properties, i.e. what level of details are considered and the time horizon (Haraldsson and Sverdrup, 2003). This is done by analysing the numerical properties of the variables to get an 'approximate' for their range, which is used while creating the SFD (this may not always be necessary if no simulation is used in the analysis). Creating an RBP from the CLD is a simple qualitative way to estimate the behaviour of the key parameters through time. The RBP is evaluated against the OBPs available from experiences, the obviously erroneous is discarded or modified. The qualitative analysis should be iterated until the desired focus has been reached.

3 Construction of a quantitative model SFD into an SD tool

The transition from a SFD and a CLD to an SDTD has been shown to be challenging (Burns, 2001; Binder *et al.*, 2004). The translation from a CLD to an SDTD is only possible if the variables have been clearly sorted into 'Agents', 'Actions', "Factors controlling actions" and 'Other conditions'. The 'Agents' are the variables identified as stocks (entities that are subject to fluxes) in the problem. The 'Actions' are the variables that have flow properties (per time unit) and the 'Controlling actions condition' variables are the coefficients calculated values (converters). Thus we have the following set of work-steps for generating the system diagram as represented by CLDs and SFDs:

1. Construct the SFD
   a. Identify the travel pathway of the entity
   b. Identify the stopping places
   c. Decide which stopping places are stocks or just junctions
   d. Indicate all movement with arrows
   e. Specify each arrow with a named action
2. Identify the components of the CLD
   a. Do the actions
      i. Place all the actions in one row in a table
      ii. Put next to them all the controlling factors for each action
      iii. Draw causal loops between the controlling factors and the actions
      iv. Check controlling factors have in their turn controls and establish ther causal links
      v. Check for back controls in each causal link
      vi. Investigate for delays in actions
   b. Put in the stocks from the SFD to start the CLD
   c. Connect all the actions with their individual causal links from the lists above
   d. Add additional factors and information transformations
3. Reiterate to the SFD

The list has been summarized in Fig. 2 and 3. Sorting up the actions is a particularly important step. Actions occur on different scales, but also within separate spheres with different communication properties. Sort them according to:

1. Physical actions that affect the moveable entities
2. Physical actions that affect mental states or entities
3. Physical actions that affect actions
4. Mental actions that affect internal states
5. Parameter transformations

It is of particular value to recognize that when mental entities or states are involved, then the mental state of a being can only affect internal mental entities directly within the same mind, whereas a mental state in one mind, but to affect an other being it must precipitate a physical action that in turn will transfer the signal by physical means to that other mind, affecting its mental state. The factors controlling actions are often state readings on stocks or entities, or the recording of actions. Decisions also have a special status. They are important as they often start with a mental parameter and at some threshold or limit, initiate an event or action, mental or physical. Great care should be taken to identify such nodes where these processes occur and to determine by which rules they most likely operate.

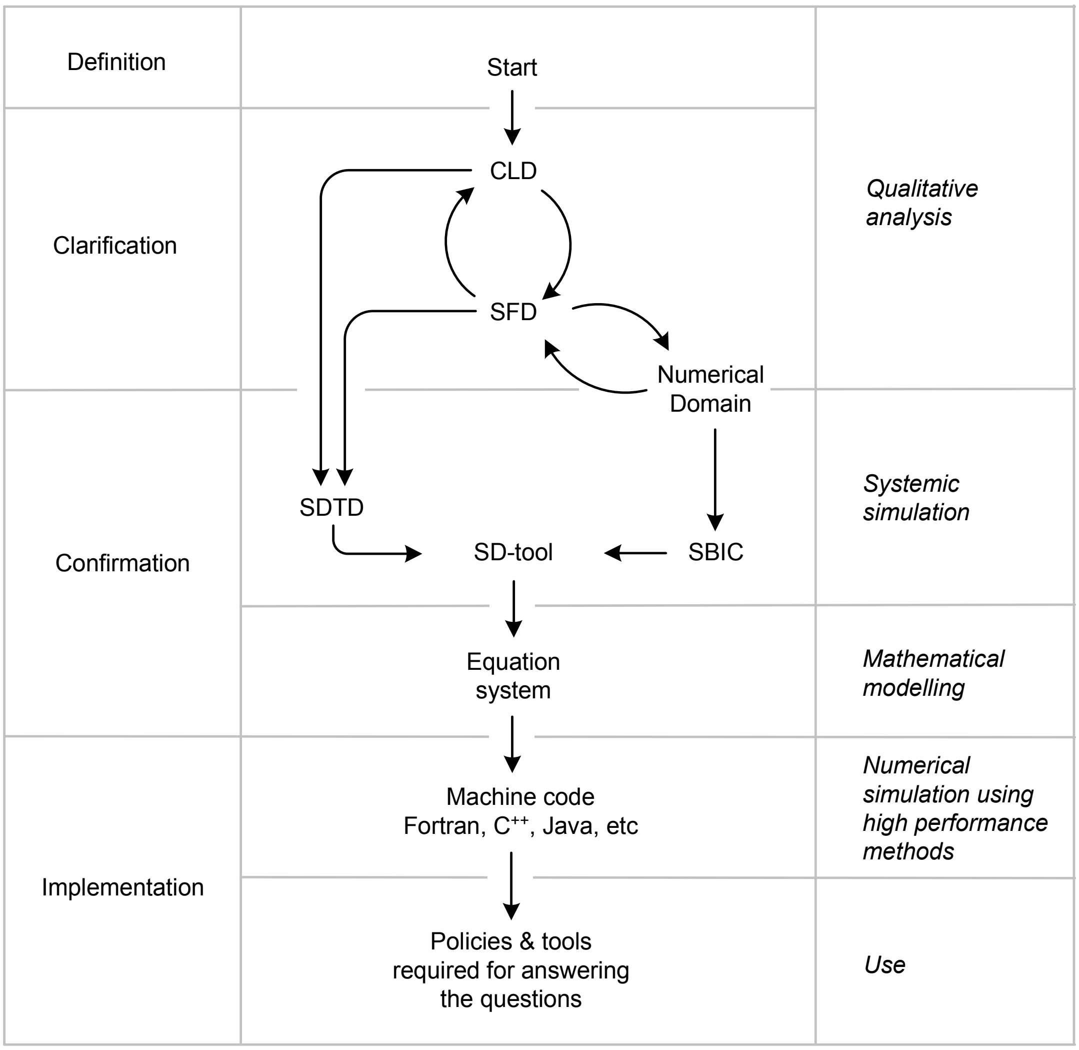


Fig. 2: The different steps of moving from, question to model in the definition to implementation dimension, showing the iterativeness of the work.

The next thing to think about is delays inside the system. Delays are created in three ways, either through:

1. Buffering mechanism limitation such as a stock that takes time to be filled or emptied.
2. Kinetic limitation, a process may proceed at a limited rate of reaction progress or rate limitation in a transformation process. This is also called a bottleneck when a transfer capacity limitation is present.
3. The transmission may be limited. When transport systems are considered, the actual transfer from one location to another may take time.

The delay may also be caused by any combinations of these. Even if we nominally have conditions that would allow for equilibrium, this may not be able to install itself instantly, and thus there may be delay. Delays are important for creating oscillations when there are feedbacks in the system (Prigogine 1980), though response surface bifurcations may also play an important role. If several delays are present in dependent systems with feedbacks, the oscillations may become very complex and despite underlying systems of order, the integrated system output behavior may appear chaotic (Prigogine and Stengers 1985). Both buffering delays and kinetic delays are commonly occurring in earth systems (Ammerman and Cavalli-Sforza 1972, White and Brantley 1995, den Elzen 1994, Lasaga 1997). The process is repeated until the CLD and SFD is found to be good by testing RBPs against available types of OBPs. These are then the construction drawings for building the SDTD diagram in the chosen tool.

	Question	Definition	Clarification	Confirmation	Implementation
Nouns and names	Who is the actor? What is being acted upon	Actors Entities	Stock	SFD	
Verbs	What are the actions? (who owns the action?)	Actions			
	What controls actions?	Controls or other actions	Action- control single CLD		
	What are the decisions and transformations? (and their control)	Decisions, decision control	Rule or diagram		
Structures	What does the system look like?			CLD SFD Revise	
	What should the Stella design look like?				SDTD

Fig. 3 Summary of the System Analysis and Systems Dynamics workflow developed by the authors. This workflow is a result of iterative development and testing in practical teaching in the systems analysis course in the LUMES Programme at Lund University during the period 1997-2005. This is used by the students as a roadmap to aid their project work progress and help them apply the necessary rigor to their work.

4. Scenario analysis and evaluation of the model and hypothesis

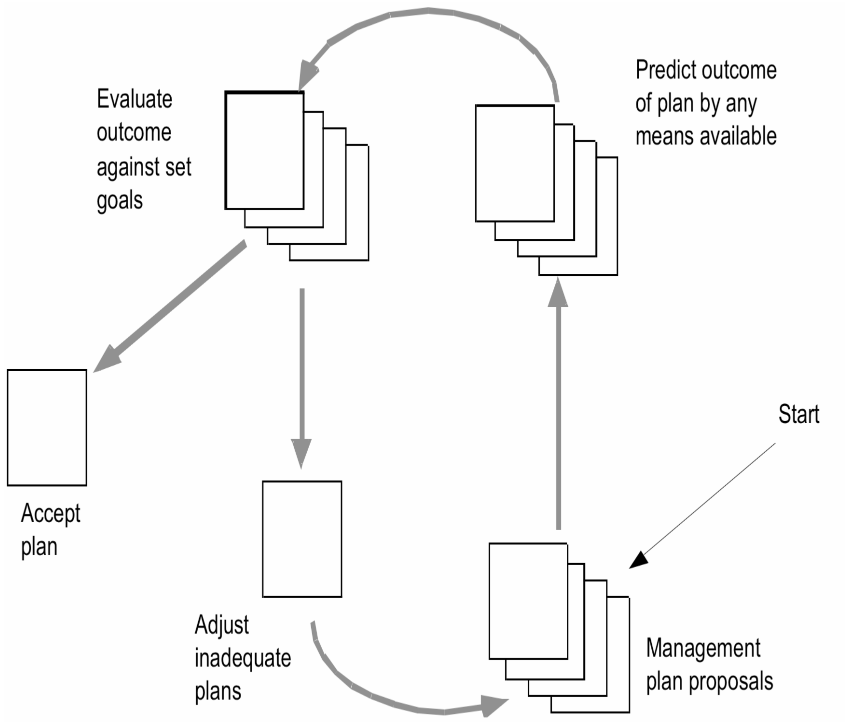
Following the transition of the CLD and the SFD into the SDTD, the SD-tool is used to test the numerical assumptions and limitation in the model. Scenarios and predictions are run. Sensitivity analysis can be used to check the model performance and accuracy. The model results are tested and evaluated against the original question in order to see if the output produces results that require redefinition of the issue as illustrated in Fig. 1. When observations from the system state are available, then these data are very important for the field test, where the models quantitative performance may be assessed. The evaluation of the model results will raise new questions on the problem and may generate a totally new insight into the issue, and thus facilitate that the whole process is revised iteratively. The iteration process in the modelling effort is important, since nearly no model is completed in the first round but several iterations are needed. When the model produces results that answer the questions and shows clear principles on assumptions and coefficients, the model equations can be extracted and programmed into code, i.e. Fortran, C^{++}, Java, etc.

When what we have discussed above is transformed into the teaching message given to students, we get the table shown in Fig 3. However, this works for any other situation as well, it is generic. This workflow is a result of iterative development and testing in practical teaching in the systems analysis course in the LUMES Programme at Lund University during the period 1997-2005. The process follows the learning loop principle by asking a set of key questions. The agents are identified. The entities moved or acted upon are identified in the next step, the actions taking place are identified. Using this information, the SFD is drawn, and each arrow between boxes are given a name and the action identified. This normally leads to more actions being identified, and sometimes to the identification of intermediate action steps. Then the actions are carried into an actions list and a list of controls for each of them are made. Then the decisions can be identified, and these are the mental actions, in contrast to physical actions. Single causal connections are established for each action and all of its controls. From these components the CLD is constructed and compared with the SFD. When these are totally inter-consistent, then the SDTD is drawn on paper, *before* the model is put into the Systems Dynamics tool. Only when the paper drawing of the SDTD is ready, is the computer tool started.

5. Discussion

Building a computerized model version is a continuation from the mental model. The workflow is designed to transform thought to images on paper that subsequently can easily converted to the required SDTD of a particular SD tool. The SDTD can only be developed when the mental model (Transformed to structural and relational maps like CLDs and SFDs) has been tested and the necessary sorting has been performed. Either the SFD or the CLD comes first, but the progressive development is iterative according to the learning loop paradigm. The workflow in model development towards implementation has been summarised in Fig. 1, where each part serves as a checkpoint for the model builder. The first part consists of Problem statement where problem and symptoms, states and events are identified. The second Part is the identification of properties of the variables into Agents, actions, and controlling factors for actions and other imposed conditions. Furthermore, the sorting of these into first an SFD and subsequently a CLD by using the SFD and the links established for all actions present. The third part is the testing and exploring of the CLD and SFD structures. The fourth part is the transfer of the CLD and SFD into a SDTD model in a SD-tool. The fourth part is the evaluation and analysis of the simulations created out with the SD-tool. The result outputs are evaluated and checked against the initial issue and documented if the user is satisfied with the results. Any discrepancies in the model output against the initial question will require a redefinition of the issue and new question. The group modelling procedure that in instrumental for the mental development process goes through four phases; Definition, Clarification, Confirmation and Implementation, and it is important to pay attention to each step in its turn (Gramstad 2004, Haraldsson and Sverdrup 2005, Haraldsson et al 2005). Each phase results in a completion of a task that modelling procedure moves from the conceptual model into programmed code. The process is dynamic through the first three phases, and this is where the workflow in Fig. 1 is used iteratively. Each step is a continuation of previous work, e.g. one cannot start running scenarios unless some sort of mental model exists. Similarly the creation of an SDTD in the second step is integrated as such that the CLD is first created by the problem definition but later adjusted by the SDTD during the construction of the simulation. The model evaluation in the third step will check if the problem is correctly represented and/or if further reiteration is required for the question posed for the problem. A summary of the implementation of model predictors in planning and design processes have been shown in Fig. 4 (Sverdrup et al. 2002). It also becomes an iterative learning process, where a designed plan is

Fig. 4: *Summary of the implementation of model predictors in planning and design processes. It also becomes an iterative learning process, where a plan is also modelled so that predicted output can be compared to the intended goals. Only those plans that are predicted to yield a result sufficiently close to the intended goal will be kept, all others are either changed or scrapped.*



also modelled so that predicted output can be compared to the intended goals. Only those plans that are predicted to yield a result sufficiently close to the intended goal, will be kept, all others are either changed or scrapped. This is adaptive management as defined by Senge (1990).

6. Conclusion

The most important aspect of the process is to systematically adhere to the principles of the learning loop, sometimes called the adaptive learning process and to be totally consistent in all system maps created, be it SFD, CLD or SDTD. There are no maybe's on modelling and therefore the issue of totality in consistency between each step is the issue that decides between success or failure. In the adaptive learning process, systems analysis repeats itself during systems dynamics and finally during model implementations and creation of design.

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